(4)

OFFICE OF NAVAL RESEARCH

Contract N00014-86-K-0043

TECHNICAL REPORT No. 108

Dynamics of an M-Level Atom Interacting with Cavity Fields:
Properties of Photon Statistics

by

Fu-li Li, Xiao-shen Li, D. L. Lin and Thomas F. George

Prepared for Publication

in

Physical Review A

Departments of Chemistry and Physics
State University of New York at Buffalo
Buffalo, New York 14260

August 1989

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1a. REPORT SECURITY CLASSIFICATION Unclassified	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; distribution unlimited
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S) UBUFFALO/DC/89/TR-108	5. MONITORING ORGANIZATION REPORT NUMBER(S)
6a. NAME OF PERFORMING ORGANIZATION Depts. Chemistry & Physics State University of New York 6b. OFFICE SYMBOL (If applicable)	7a. NAME OF MONITORING ORGANIZATION
6c. ADDRESS (City, State, and ZIP Code) Fronczak Hall, Amherst Campus Buffalo, New York 14260	7b. ADDRESS (City, State, and ZIP Code) Chemistry Program 800 N. Quincy Street Arlington, Virginia 22217
8a. NAME OF FUNDING/SPONSORING ORGANIZATION Office of Naval Research 8b. OFFICE SYMBOL (If applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER Contract N00014-86-K-0043
8c. ADDRESS (City, State, and ZIP Code) Chemistry Program 800 N. Quincy Street Arlington, Virginia 22217	10. SOURCE OF FUNDING NUMBERS PROGRAM ELEMENT NO. / PROJECT NO. / TASK NO / WORK UNIT ACCESSION NO.

11. TITLE (Include Security Classification)

Dynamics of an M-Level Atom Interacting with Cavity Fields: Properties of Photon Statistics

12. PERSONAL AUTHOR(S)

Fu-li Li, Xiao-shen Li, D. L. Lin and Thomas F. George

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
	FROM ______ TO ______	August 1989	25

16. SUPPLEMENTARY NOTATION

Prepared for publication in Physical Review A

17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB-GROUP	M-LEVEL ATOM; CAVITY FIELD; DYNAMIC INTERACTION; PHOTON STATISTICS; PHOTON ANTIBUNCHING; PROBABILITY DISTRIBUTION

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

For a system of an M-level atom interacting with cavity fields, the statistical properties of the field are investigated numerically. The variation of photon antibunching and probability distribution with the atomic level number and initial field intensity are discussed for both resonance and off-resonance cases.

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT ☒ UNCLASSIFIED/UNLIMITED ☒ SAME AS RPT. ☐ DTIC USERS	21. ABSTRACT SECURITY CLASSIFICATION Unclassified
22a. NAME OF RESPONSIBLE INDIVIDUAL Dr. David L. Nelson	22b. TELEPHONE (Include Area Code) (202) 696-4410 22c. OFFICE SYMBOL

DD Form 1473, JUN 86 Previous editions are obsolete.

SECURITY CLASSIFICATION OF THIS PAGE

UNCLASSIFIED

Physical Review A, in press

Dynamics of an M-level atom interacting with cavity fields: Properties of photon statistics

Fu-li Li
Department of Physics
Xian Jiao Tong University
Xian, Shaanxi, P. R. China

Xiao-shen Li
Center of Theoretical Physics
Chinese Center of Advanced Science and Technology (World Laboratory)
P. O. Box 8730
Beijing 100080, People's Republic of China

and

Shanghai Institute of Metallurgy, Chinese Academy of Sciences
Shanghai, People's Republic of China

D. L. Lin and Thomas F. George
Department of Physics & Astronomy
239 Fronczak Hall
State University of New York at Buffalo
Buffalo, New York 14260

Abstract

For a system of an M-level atom interacting with cavity fields, the statistical properties of the field are investigated numerically. The variation of photon antibunching and probability distribution with the atomic level number and initial field intensity are discussed for both resonance and off-resonance cases.

1988 PACS Nos.: 32.80.-t, 42.50.-p, 42.50.Dv

I. Introduction

There are two aspects of the problem of an atom interacting with radiation fields in a cavity, the dynamical behavior of the atom during the interaction process and the evolution of the coherence and statistical properties of the radiation field. Although a large amount of work on atomic properties has been carried out in the Jaynes-Cummings (JC) model,[1] relatively less attention has been paid to the field properties.

Early studies of the first-order correlation function in the JC model revealed that the disparity between $\langle a^\dagger(t)a(t)\rangle$ and $\langle a^\dagger(t)\rangle\langle a(t)\rangle$ increases with time if the field is initially in the coherent state.[2] Diagonal elements of the field density matrix were explicitly calculated later.[3] Only recently were effects on the nonclassical behavior of the atom and the field due to the cavity loss discussed.[4] The upper and lower bounds of the Q-value in the JC model were given analytically,[5] and an analysis of these bounds show that the larger the amplitude of the initial coherent state, the less sub-Poisson (or super-Poisson) the photon statistics can become.

A direct generalization of the JC model is the system of a three-level atom interacting with one-mode or two-mode cavity fields. The off-resonance behavior of the cavity fields has been investigated by two of the present authors and others.[6,7] It was discovered in Ref. 6 that the initially coherent field does not lose its coherence right after the interaction with the atom takes place when the interaction is off resonance. Instead, it may recover coherence almost periodically. As a matter of fact, the field can remain coherent for a long time if the detunings are sufficiently far away from the resonance. The photon probability distribution and fluctuation are discussed in detail in Ref. 7, where it is found that for a one-mode Λ-type atom, sub-Poisson and super-Poisson distributions appear alternatively as time develops, and for a two-mode Λ-type the distribution is always super-Poisson. Furthermore, photons involved in the former case exhibit antibunching phenomena and in the latter case exhibit bunching phenomena.

The photon statistics has also been studied in another case in which an atom with one common upper and N-1 lower levels interacts with N-1 modes of a cavity field.[8] A numerical calculation was performed for resonance interaction with initially one mode (called the pumping mode) of coherent light present. Once the interaction takes place, all the other modes (called signal modes) start to build up. Photons in these signal modes are found to show sub-Poisson distribution and hence exhibit antibunching all the time.

As the observation of the one-atom maser has become practical,[9] and since the atom is excited to high levels with principal quantum number in the range of 30 ~ 40, it is inevitable that multiphoton processes are involved. In fact, a micromaser based on degenerate two-photon transitions is already realized.[10] Theoretically, however, there does not seem to have been sufficient attention given to multiphoton processes in the literature thus far. In two recent papers,[11,12] the present authors considered a single M-level atom interacting with cavity fields with arbitrary detunings. Time evolution of atomic level occupation probabilities, mean photon number and field squeezing have been investigated in detail. Their dependence on the atomic level number as well as on the initial field intensity has been discussed. Here in this paper, we discuss the photon probability distribution and fluctuation and their variations with various parameters.

An outline of the theory is given in Sec. II. Results of the numerical calculation are presented and discussed in Sec. III, and concluding remarks are given in Sec. IV.

II. Theory

The general formalism of the theory can be found in Ref. 11 (hereafter referred to as I), and we only outline the essentials here. We consider a cascade atom with M energy levels as shown in Fig. 1. The total Hamiltonian is, in the rotating wave approximation,

$$H = \hbar\Omega a^\dagger a + \sum_{i=1}^{M} \hbar\omega_i A_i^\dagger A_i + \sum_{i=1}^{M-1} \lambda_i A_{i+1}^\dagger A_i a + \text{h.c.} \tag{1}$$

where the operator $a^\dagger$ creates a photon, $A_i^\dagger$ creates an atom in the i-th level, and λ_i are the atom-field coupling constants. Our discussion will be limited, for simplicity, to processes involving only a one-photon transition between adjacent atomic levels.

We define the total excitation number operator

$$\hat{N} = a^\dagger a + \sum_{i=1}^{M} i A_i^\dagger A_i \quad , \tag{2}$$

which is the sum of the photon number and atomic excitation number operators. It can readily be verified that $[H,\hat{N}] = 0$, i.e., $\hat{N}$ is a constant of motion.

If we are only interested in the particular case in which the atom is initially in its highest level, then we need only consider that part of the Hilbert space involving state vectors corresponding to $N \geq M$, where N is the eigenvalue of the operator $\hat{N}$. This is a consequence of the fact that N is a conserved quantity.

Consider the state

$$|i,n\rangle = |i\rangle|n\rangle \tag{3}$$

in which there are n photons in the field and the atom is in the i-th state. The subspace corresponding to $N = M + n$ is spanned by the state vectors $|M,n\rangle$, $|M-1,n+1\rangle$, $\ldots|i,n+M-i\rangle$, $\ldots|1,n+M-1\rangle$, where n is the photon number in the field and can take any positive integral value. Since state vectors in different subspaces are necessarily orthogonal, the total Hamiltonian can be diagonalized in every subspace.

An arbitrary state in the subspace corresponding to N can be expressed as

$$|\phi_n\rangle = \sum_{i=1}^{M} C_{i,n+M-i}|i,n+M-i\rangle \quad , \tag{4}$$

where the expansion coefficients $C_{i,n+M-i}$ satisfy the stationary-state Schrödinger equation

$$\sum_{i'=1}^{M} (H_{ii}\delta_{ii'} + H_{ii'} - E\delta_{ii'})C_{i',n+M-i'} = 0 \quad . \tag{5}$$

The matrix elements in (5) are given by

$$H_{ii} = \langle i,n+M-i|H|i,n+M-i\rangle = (n+M-1)\hbar\Omega + \hbar\omega_1 - \sum_{j=1}^{i-1} \Delta_j \tag{5a}$$

$$H_{ii'} = \langle i,n+M-i|H|i',n+M-i'\rangle$$

$$= \lambda_{i'} \sqrt{n+m-i'}\ \delta_{i,i'+1} + \lambda_{i'-1} \sqrt{n+M-i'+1}\ \delta_{i,i'-1} \quad , \qquad i \neq i' \quad (5b)$$

Here we have defined the detuning parameters

$$\Delta_i = \hbar\Omega - \hbar(\omega_{i+1} - \omega_i) \quad , \qquad i = 1, 2, \ldots, M-1 \quad . \tag{6}$$

The energy eigenvector $|\phi_{n\sigma}>$ and the corresponding eigenvalue $E_{n\sigma}$ are determined by

$$H|\phi_{n\sigma}> = E_{n\sigma}|\phi_{n\sigma}> \tag{7a}$$

$$|\phi_{n\sigma}> = \sum_{i=1}^{M} C^{\sigma}_{i,n+M-1}|i,n+M-i> \quad . \tag{7b}$$

The subscript σ in (7a) labels the eigenstates in the subspace in question.

If the atom is assumed to be initially in the M-th level, then for all time $t > 0$ the system can only be found in subspaces with $N \geq M$. There are M eigenstates of the type (7b) in every subspace. Hence the orthonormality condition is

$$\sum_{i=1}^{M} C^{\sigma'}_{i,n+M-i}\, C^{\sigma}_{i,n+M-i} = \delta_{\sigma'\sigma} \quad , \tag{8}$$

and the completeness relation is

$$\sum_{n=0}^{\infty} \sum_{\sigma=1}^{M} |\phi_{n\sigma}><\phi_{n\sigma}| = 1 \quad . \tag{9}$$

We can now solve the equation of motion for the density matrix. Its matrix element between energy eigenstates satisfies the equation

$$\frac{\partial}{\partial t} \rho_{n\sigma,n'\sigma'}(t) = - \frac{i}{\hbar} (E_{n\sigma} - E_{n'\sigma'}) \rho_{n\sigma,n'\sigma'} \quad , \tag{10}$$

whose solution can be put in the form

$$\rho_{n\sigma,n'\sigma'}(t) = \rho_{n\sigma,n'\sigma'}(0)\, e^{-\frac{i}{\hbar}(E_{n\sigma} - E_{n'\sigma'})t} \quad . \tag{11}$$

The initial matrix element in (11) is given by

$$\rho_{n\sigma,n'\sigma'}(0) = \rho_{nn'} (C^{-1})^{M}_{\sigma,n+M-\sigma} (C^{-1})^{M}_{\sigma',n+M-\sigma'} \tag{12}$$

where C^{-1} is the inverse matrix of the transformation defined in (4) and $\rho_{nn'}$ is the initial density matrix element of the field.

The normalized intensity correlation function of the field is defined as

$$g^{(2)}(t) = \langle a^{\dagger 2} a^2 \rangle / \langle a^\dagger a \rangle^2 \quad , \tag{13}$$

where

$$\langle n \rangle = \langle a^\dagger a \rangle = Tr(\rho a^\dagger a)$$

$$= \sum_{n=0}^{\infty} \sum_{i=1}^{M} (n+M-i) \sum_{\sigma=1}^{M} \sum_{\sigma'=1}^{M} C^{\sigma}_{i,n+M-i}\, C^{\sigma'}_{i,n+M-i}$$

$$\times\ \rho_{n\sigma,n\sigma'}(0)\ \cos\left[\frac{(E_{n\sigma}-E_{n\sigma'})t}{\hbar}\right] \tag{14}$$

$$\langle a^{\dagger 2}a^{2}\rangle = \sum_{n=0}^{\infty}\sum_{i=1}^{M}(n+M-i)(n+M-i-1)$$

$$\times\sum_{\sigma=1}^{M}\sum_{\sigma'=1}^{M}C^{\sigma}_{i,n+M-i}\ C^{\sigma'}_{i,n+M-i}\ \rho_{n\sigma,n\sigma'}(0)\ \cos\left[\frac{(E_{n\sigma}-E_{n\sigma'})t}{\hbar}\right]\ . \tag{15}$$

The probability of finding m photons in the field at time t is given by

$$p_m(t) = \sum_{n=m-M+1}^{m}\langle i,n+M-i|\rho|i,n+M-i\rangle\ , \tag{16}$$

where $i = n+M-m$ and $n \geq 0$. Taking the inverse transformation of (7b) and plugging it into (16), we find

$$p_m(t) = \sum_{n=m-M+1}^{m}\sum_{j=1}^{M}\sum_{j'=1}^{M}(C^{-1})^{n+M-m}_{j',n+M-j'}\ (C^{-1})^{n+M-m}_{j,n+M-j}$$

$$\times\ \rho_{nj,nj'}(0)\ \cos\left[\frac{(E_{nj}-E_{nj'})t}{\hbar}\right]\ , \tag{17}$$

where we have made use of (11). It is then not difficult to prove that

$$\sum_{m=0}^{\infty}p_m(t) = \sum_{n=0}^{\infty}\sum_{j=1}^{M}\rho_{nj,nj}(0) = 1\ . \tag{18}$$

The statistical properties of the field are completely described by Eqs. (13) and (17), which we shall discuss in the following section.

III. Results and discussion

Throughout this paper, we take $\hbar = 1$ in our numerical calculation. The above formulas are derived on the assumption the atom is initially in its highest level M.[11] We now assume further that the field is initially in the coherent state with mean photon number $\bar{n}$. Thus the diagonal matrix element of the initial density matrix of the field is

$$\rho_{nn} = \frac{\bar{n}^n}{n!} e^{-\bar{n}} \quad . \tag{19}$$

As is well known, when the field is strictly in the coherent state, the equal-time second-order correlation function is $g^{(2)}(t) = 1$. When $g^{(2)}(t) < 1$, the field exhibits antibunching, and when $g^{(2)}(t) > 1$, the field exhibits bunching. The time evolution of the correlation function calculated from (13) is presented in Figs. 2 and 3 for various M and $\bar{n}$. Resonance conditions $\Delta_i = 0$ have been assumed here for simplicity. It is observed that the correlation function oscillates irregularly around its initial value of 1. Thus the field exhibits alternatively bunching and antibunching as time develops. For a fixed M, this oscillation amplitude decreases with the increasing $\bar{n}$. In other words, the stronger the initial field is, the weaker the effect of bunching or antibunching becomes. Therefore, strong photon bunching or antibunching results if the initial field strength weakens. The same conclusions have been obtained for the M = 2 case.[5]

Physically, it is not difficult to understand this phenomenon. Since we have assumed that the field is in the coherent state initially, at any later time or $t > 0$, the total field is the sum of the initial field plus the radiation field of the stimulated atom. The latter acts like a modulator that causes the initial field to deviate from coherence. The smaller the $\bar{n}$, the easier the initial field is modulated. At any time $t > 0$, the total field is dominated by the stimulated radiation field which is an oscillating function of time. As a consequence, the total field oscillates between bunching and antibunching. If we compare the curves for the same $\bar{n}$ but different M, we find that the effect of antibunching decreases when the number of atomic levels increases. Similar results have also been found for a common upper N-level atom interacting with N-1 modes of cavity fields.[8]

The photon number fluctuation is directly related to the Q-parameter defined as[13]

$$Q = \frac{\langle n^2 \rangle - \langle n \rangle^2}{\langle n \rangle} - 1 \quad . \tag{20}$$

When $Q > 0$, the fluctuation is large and the photon probability distribution is super-Poisson. When $Q < 0$, the fluctuation is small and the probability distribution is sub-Poisson. The lower bound of Q is -1, corresponding to zero fluctuation, where the probability has its sharpest peak. When $Q = 0$, the photon probability has a Poisson distribution, indicating a coherent state of the field. The time evolution of the Q-parameter is presented in Figs. 6 and 7 for different M and $\bar{n}$. From these figures we can see that, similar to g(2), for fixed M the amplitude of the oscillation of Q becomes smaller when $\bar{n}$ increases, and that the photon probability approaches the Poisson distribution when $\bar{n}$ increases. For fixed $\bar{n}$, increasing M will cause the photon probability to deviate from the Poisson distribution and tend to become super-Poisson.

Since the Q-parameter is related to the normalized Glauber correlation function $g^{(2)}(0)$ by

$$Q = \langle n \rangle [g^{(2)}(0) - 1] \quad , \tag{21}$$

it is clear that photons exhibit the antibunching phenomenon whenever the probability distribution is sub-Poisson, and exhibits bunching phenomenon when the probability has a super-Poisson distribution. It should be noted that a minimum $g^{(2)}$ does not imply a minimum Q because of the factor $\langle n \rangle$ in (21), except that $\langle n \rangle$ is just in the time region with collapsed oscillation. This can be seen by comparing Figs. 2, 4, and 6 or Figs. 3, 5 and 7 with one another. We have also found that for certain $\bar{n}$ and M the field can be kept in a coherent state for a long time with $g^{(2)} \approx 1$ and $Q \approx 0$ (see Figs. 2(c) and 6(c)). This means that the initially coherent field can recover its coherence after the interaction with the atom takes place. This is in agreement with the conclusions of Ref. 6.

Next we look at the case in which the detunings are nonzero. We assume that $|\Delta_i| \neq 0$ ($i = 1, 2, \ldots, M-1$) but $\sum_{i=1}^{M} \Delta_i = 0$. That is, multiphoton transitions involving less than M-1 photons are all detuned, and only the (M-1)-fold degenerate photon transition satisfies the resonance condition. The correlation function is calculated for M = 3 and 9, $\bar{n} = 3$ and $|\Delta_i| = 0.5$ and 1.5. The results are plotted in Figs. 8 and 9. We see from these figures that for a given M, a larger detuning results in weaker antibunching but stronger bunching. This feature becomes even stronger as M becomes larger. On the other hand, when the detunings $|\Delta_i|$ are fixed, then larger M corresponds to weaker antibunching. This means that the more photons that are involved in the degenerate multiphoton transition, the weaker the antibunching becomes in the process.

In addition, we have also examined the sub-Poisson distributions of the photons with the same M but different $\bar{n}$, where we find sharper peaks in the stribution when the initital field strength is weaker or when $\bar{n}$ is smaller. ted, however, that $\bar{n}$ should be kept above a certain value, say, ≥ 3, therwise the distribution approaches the shape of a thermal distri . We have also computed the photon distribution for nonresonant cases (numerical results are not presented here), where we have found that the detunings tend to weaken the sub-Poisson and super-Poisson effects.

IV. Conclusions

We have shown that multiphoton processes lead to a minimum fluctuation in the field intensity. Although such a markedly reduced fluctuation occurs only at some particular time, it can be achieved by adjusting the velocity of the atom injected into the optical cavity, because the JC model is realized in practice by the micromaser.[9] In other words, the most stable intensity of the output field can be obtained by adjusting the duration that the atom stays within the cavity. This is also true for the squeezing of the field.[12]

Acknowledgments

This research was partially supported by the Office of Naval Research, the National Science Foundation under Grant CHE-8620274, and the Air Force Office of Scientific Research (AFSC), United States Air Force, under Contract F49620-86-C-0009. The United States Government is authorized to copy and

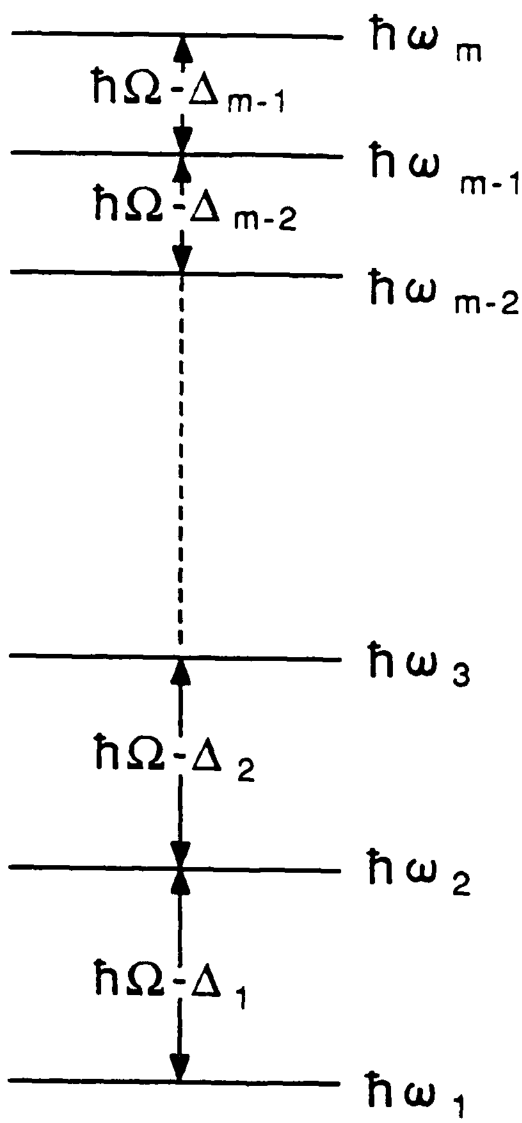
References

1. E. T. Jaynes and F. W. Cummings, Proc. IEEE 51, 89 (1963).
2. F. W. Cummir hys. Rev. A 140, 1051 (1965).
3. P. Meystre, E. Geneux, A. Quattropaniand and A. Faist, Nuovo Cimento 25B, 521 (1975).
4. R. R. Puri and G. S. Agarwal, Phys. Rev. A 33, 3610 (1986).
5. M. Hillery, Phys. Rev. A 35, 4186 (1987).
6. Z. D. Liu, X. S. Li and D. L. Lin, Phys. Rev. A 36, 5220 (1987).
7. D. L. Lin, X. S. Li and Y. N. Peng, Phys. Rev. A 39, 1933 (1989).
8. M. Kozierowski and A. S. Shumovsky, Physica 145A, 290 (1987).
9. G. Rempe, H. Walther and N. Klein, Phys. Rev. Lett. 58, 353 (1987); D. Meshhede, H. Walther and G. Müller, Phys. Rev. Lett. 54, 551 (1985).
10. M. Brune, J. M. Raimond, P. Goy, L. Davidovich and S. Haroche, Phys. Rev. Lett. 59, 1899 (1987).
11. F. L. Li, D. L. Lin, T. F. George and X. S. Li, Phys. Rev. A, in press. This paper is hereafter referred to as I.
12. F. L. Li, X. S. Li, D. L. Lin and T. F. George, J. Phys. B, in press.
13. L. Mandel, Opt. Lett. 4, 205 (1979).

Figure captions

1. Schematic diagram of the atomic levels.
2. Time evolution of the correlation function $g^{(2)}$ under resonance conditions $\Delta_i = 0$ for $M = 3$: (a) $\bar{n} = 3$, (b) $\bar{n} = 5$, (c) $\bar{n} = 10$.
3. Same as Fig. 2 except $M = 9$.
4. Time evolution of the mean photon number $\langle n \rangle$ for $\Delta_i = 0$ and $M = 3$: (a) $\bar{n} = 3$, (b) $\bar{n} = 5$, (c) $\bar{n} = 10$.
5. Same as Fig. 4, except $M = 9$.
6. Time evolution of Mandel's Q-parameter for $\Delta_i = 0$ and $M = 3$: (a) $\bar{n} = 3$, (b) $\bar{n} = 5$, (c) $\bar{n} = 10$.
7. Same as Fig. 6, except $M = 9$.
8. Time evolution of $g^{(2)}$ for $M = 3$ and $\bar{n} = 3$. The resonance conditions are not satisfied by the individual transitions, but $\sum_i \Delta_i = 0$, where $\Delta_1, \ldots, \Delta_{\frac{M-1}{2}} > 0$, $\Delta_{\frac{M+1}{2}}, \ldots, \Delta_{M-1} < 0$ $(i = 1, \ldots, M-1)$: (a) $|\Delta_i| = 0.5$, (b) $|\Delta_i| = 1.5$.
9. Same as Fig. 8 except $M = 9$.

Fig. 1



$\hbar\omega_m$
$\hbar\Omega - \Delta_{m-1}$
$\hbar\omega_{m-1}$
$\hbar\Omega - \Delta_{m-2}$
$\hbar\omega_{m-2}$
$\hbar\omega_3$
$\hbar\Omega - \Delta_2$
$\hbar\omega_2$
$\hbar\Omega - \Delta_1$
$\hbar\omega_1$

Fig 2

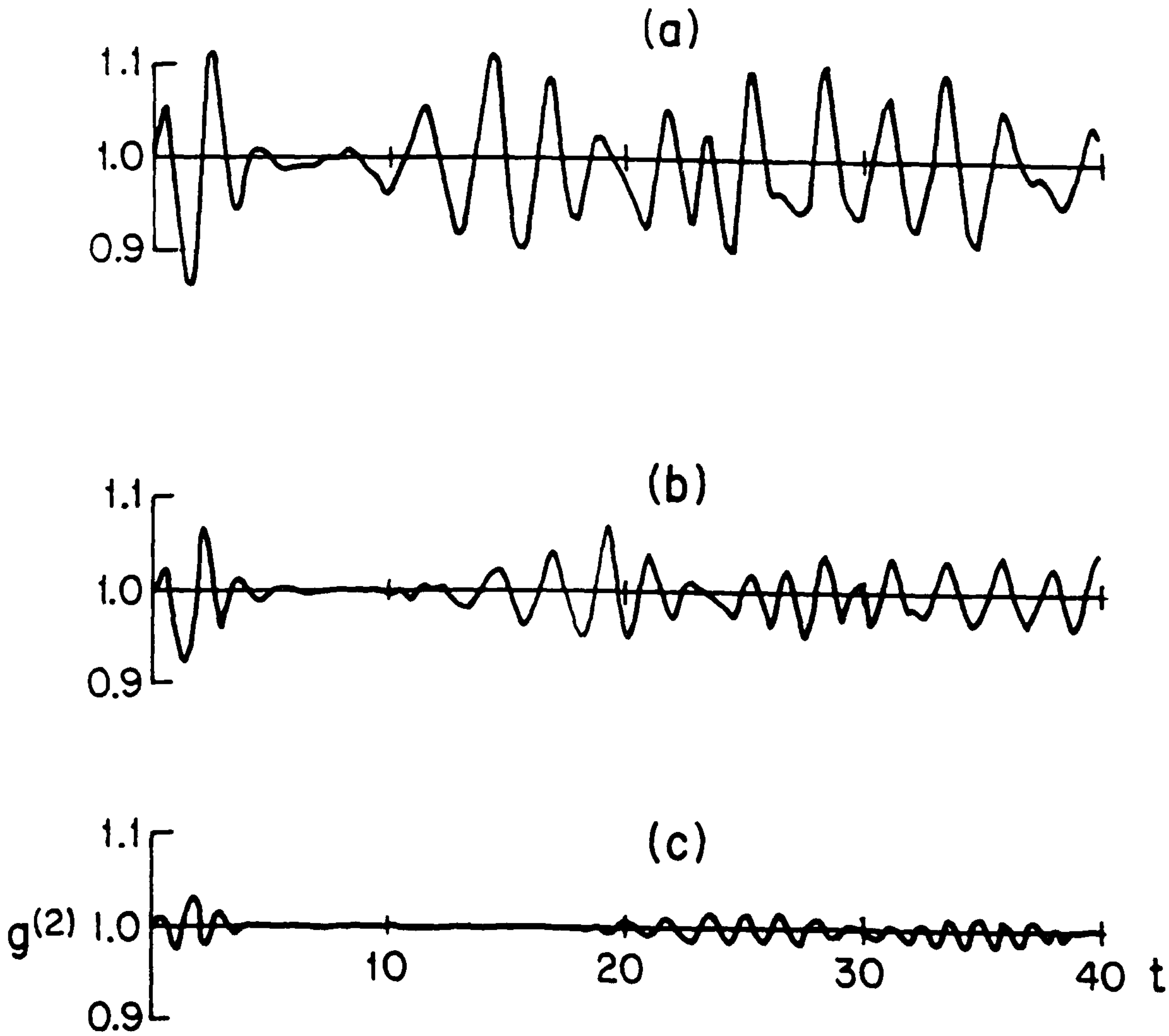


Fig. 3

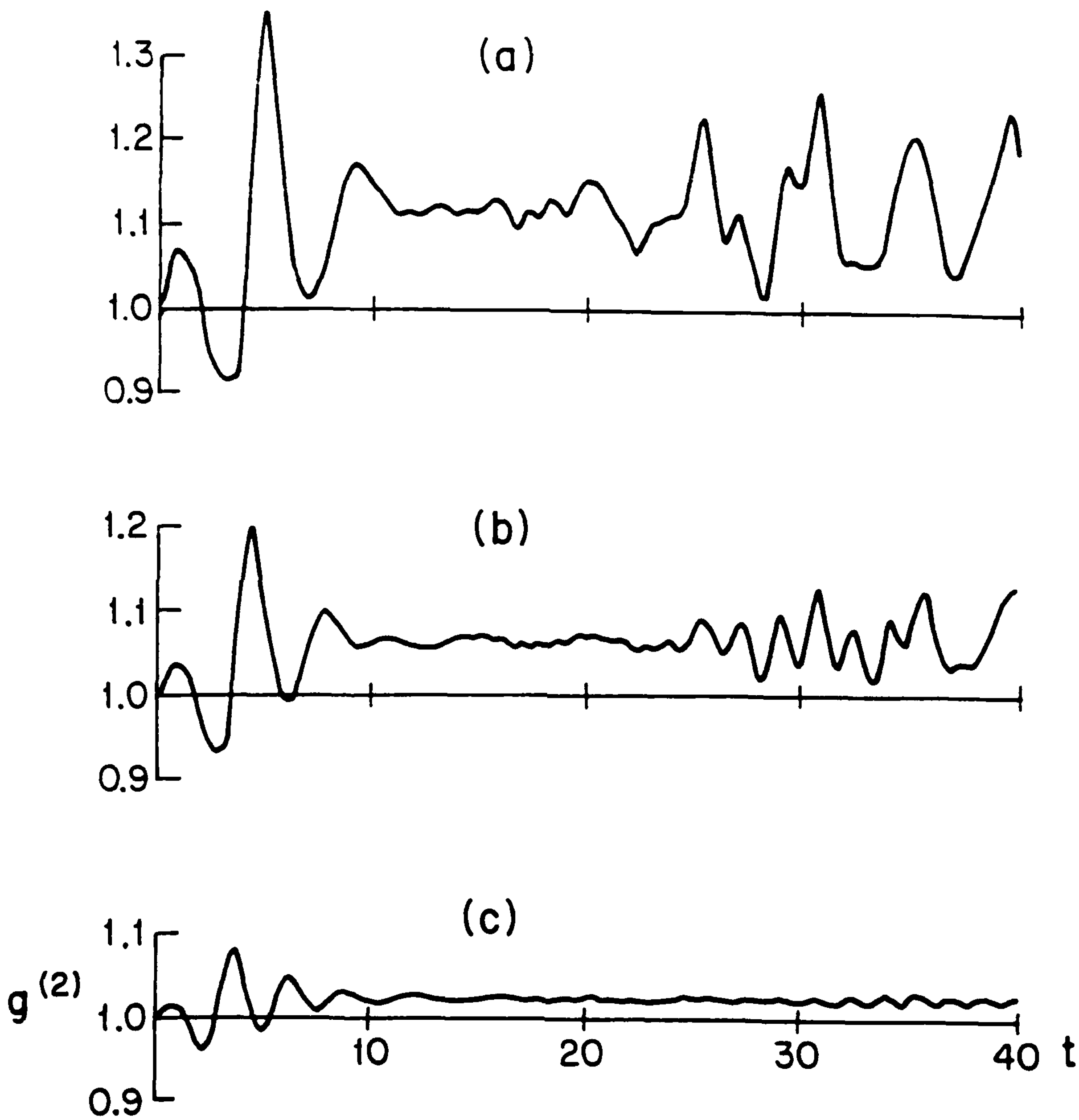


Fig. 4

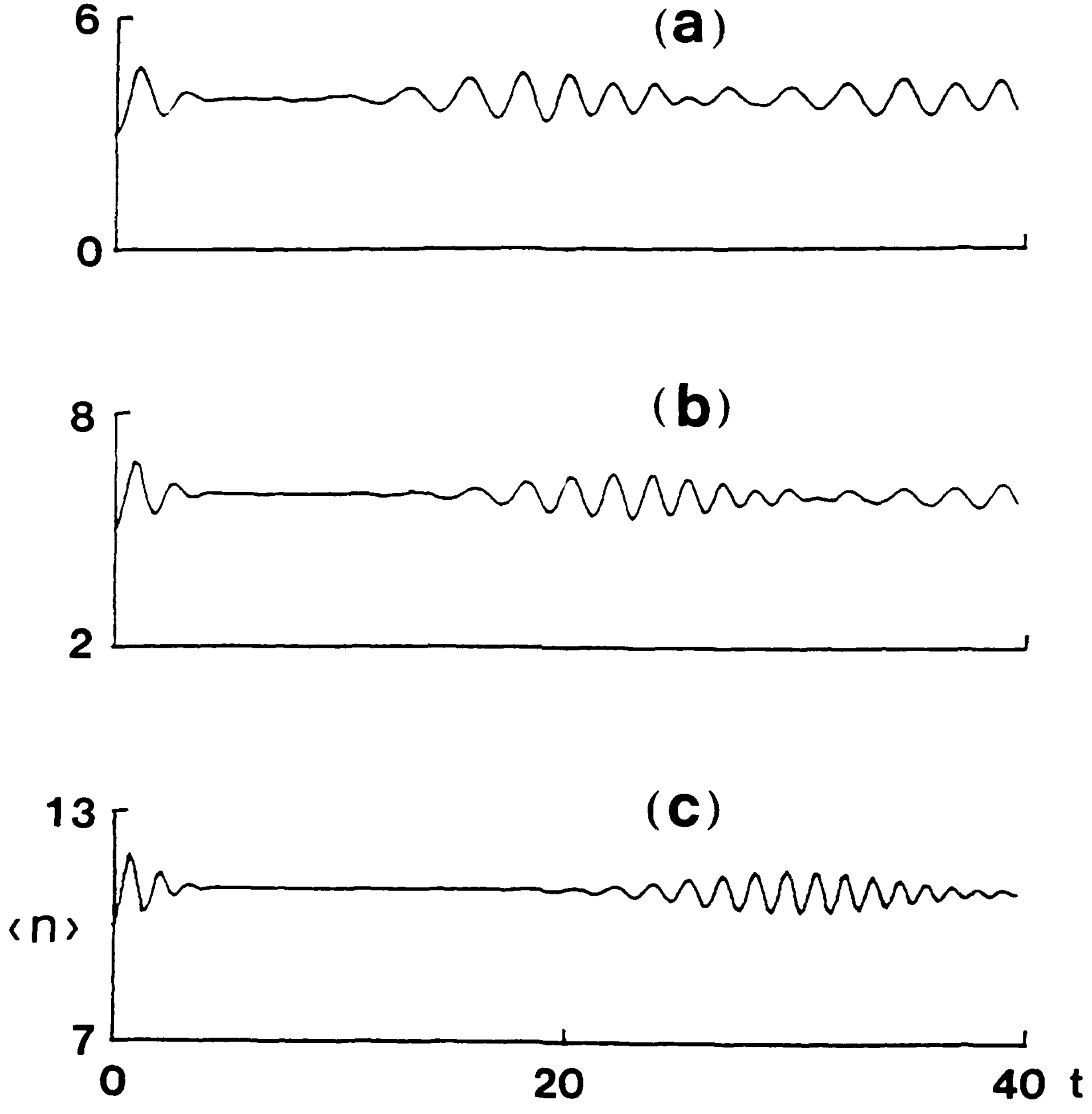


Fig. 5

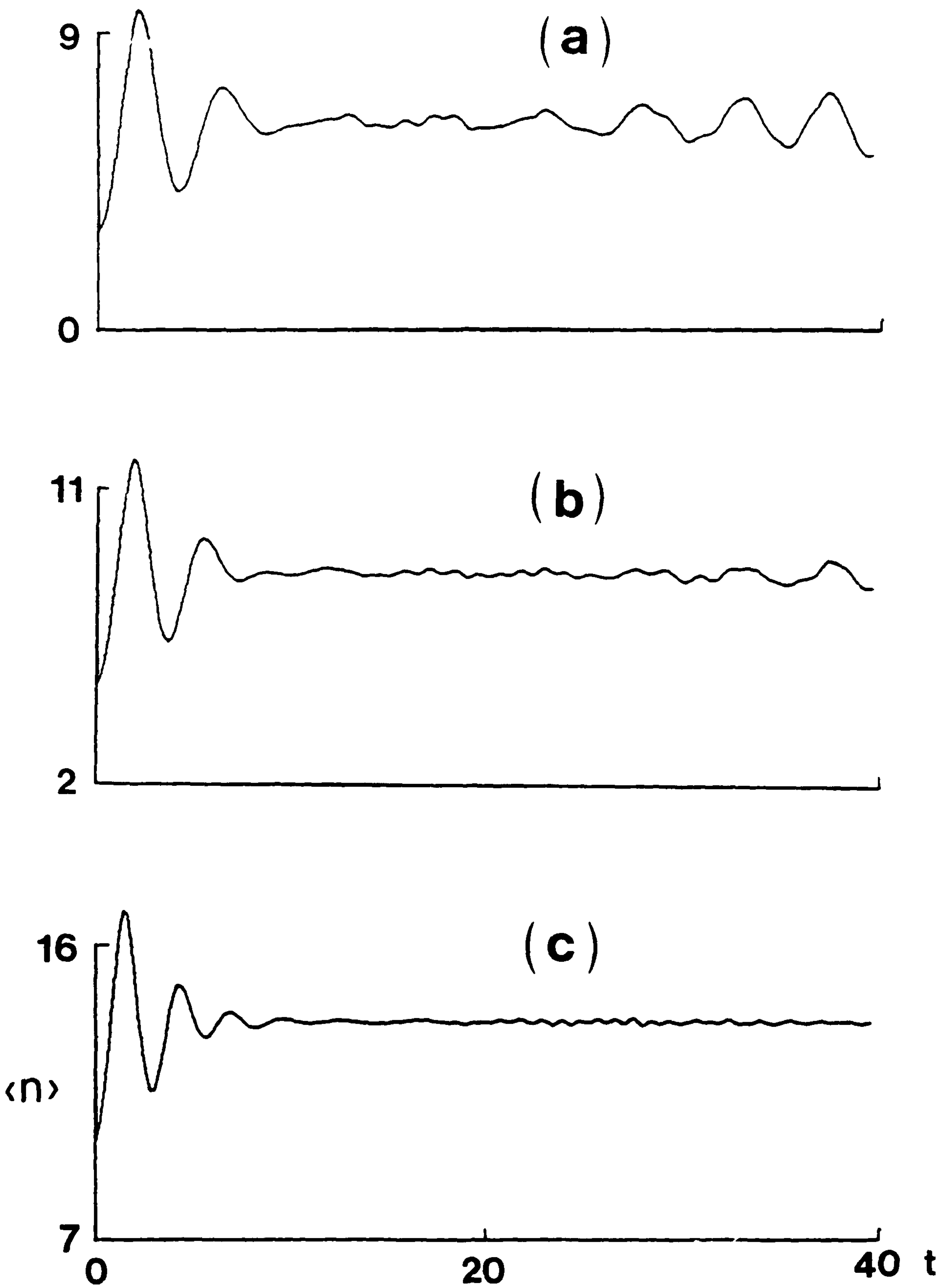


Fig. 6

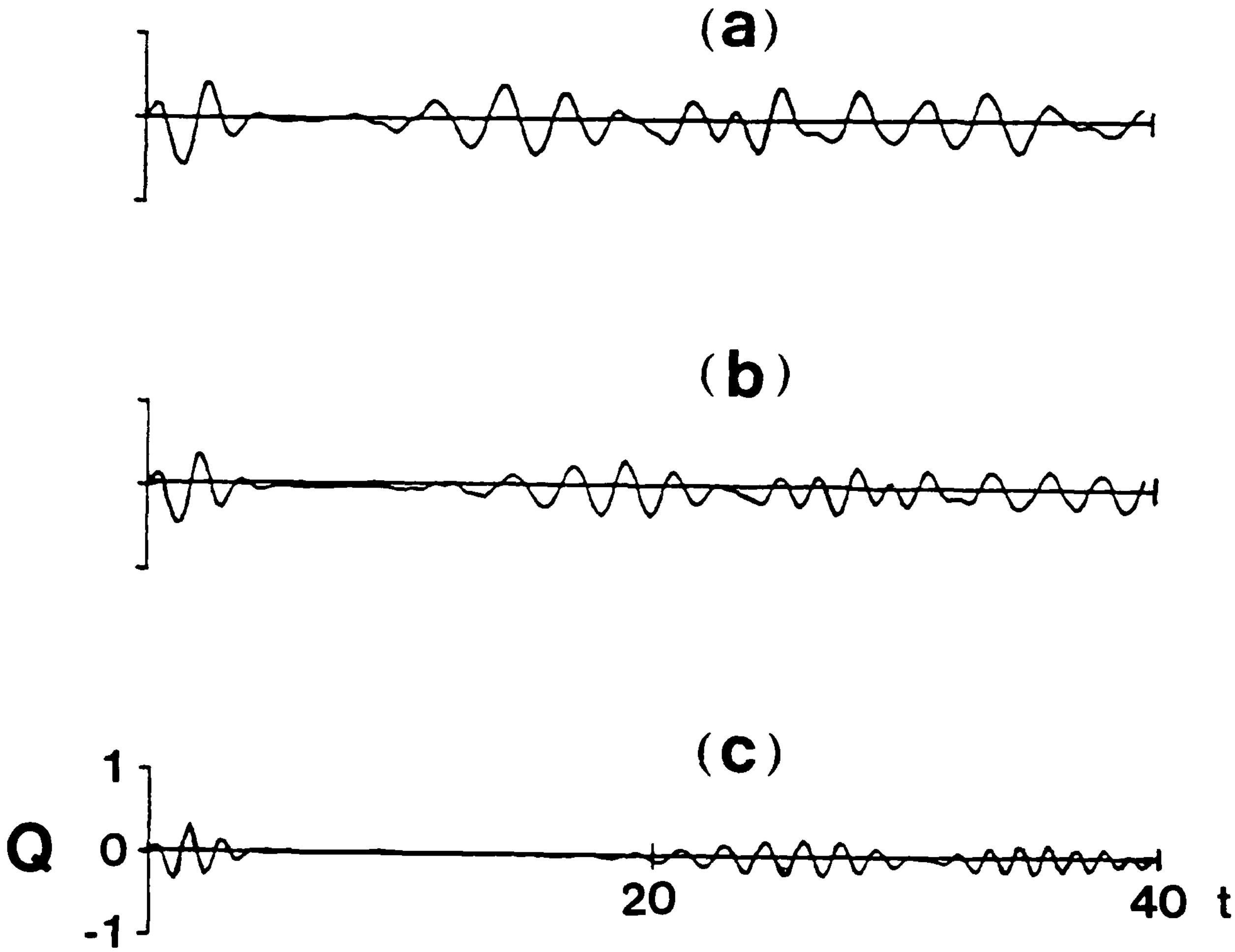


Fig 7

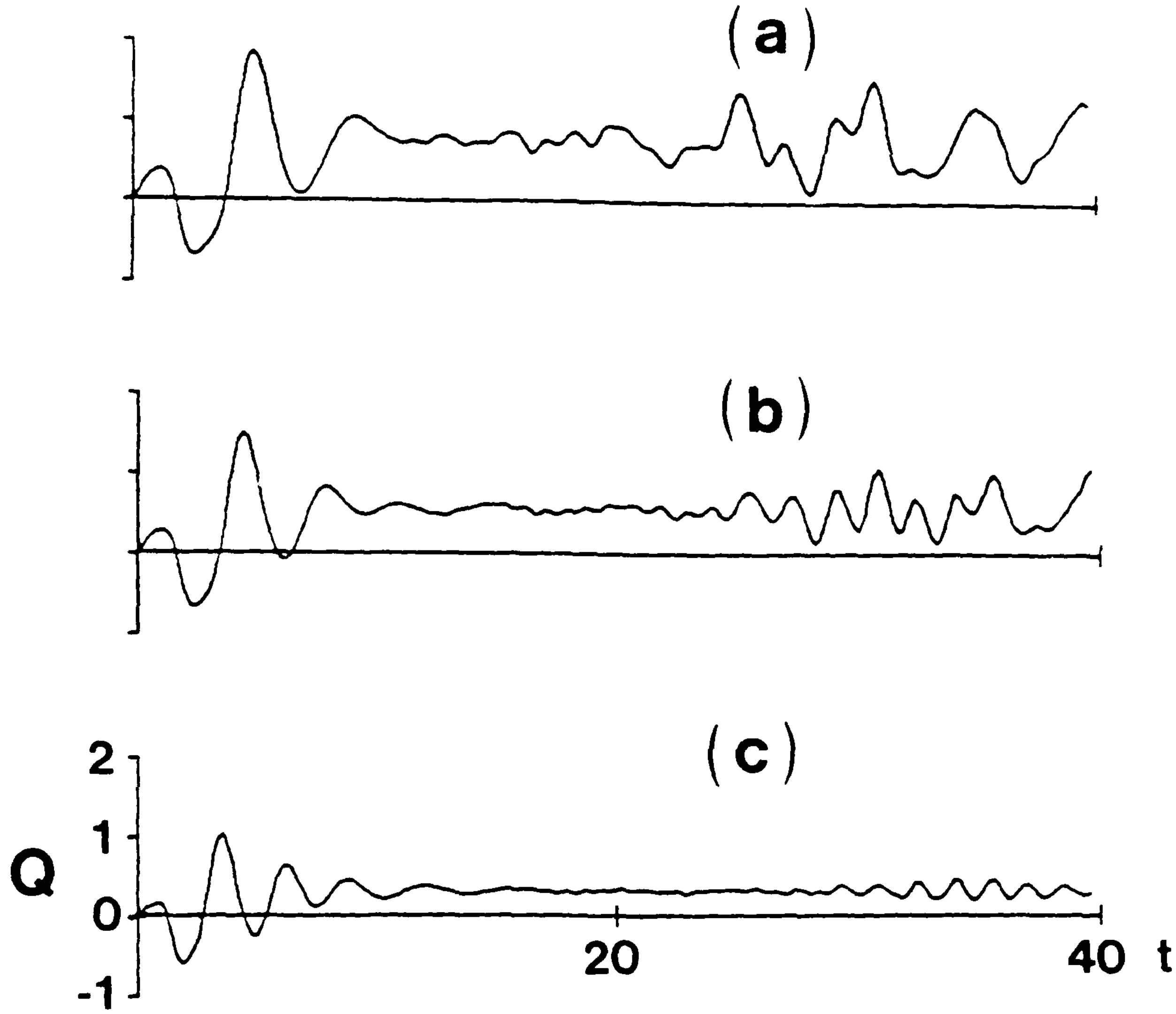


Fig 8

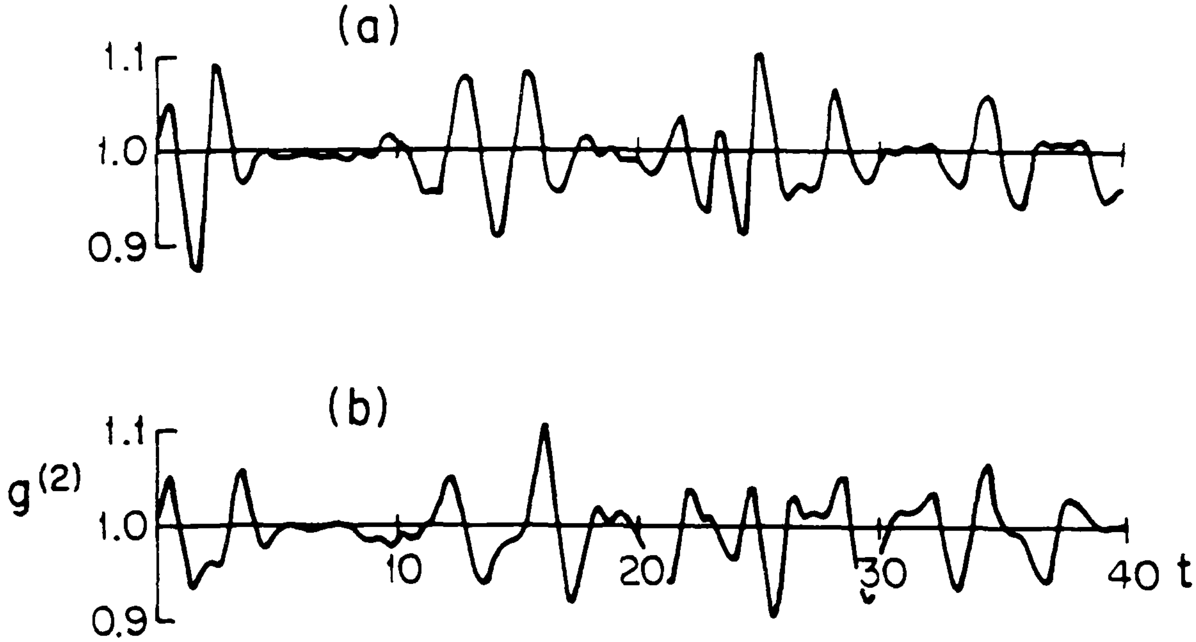
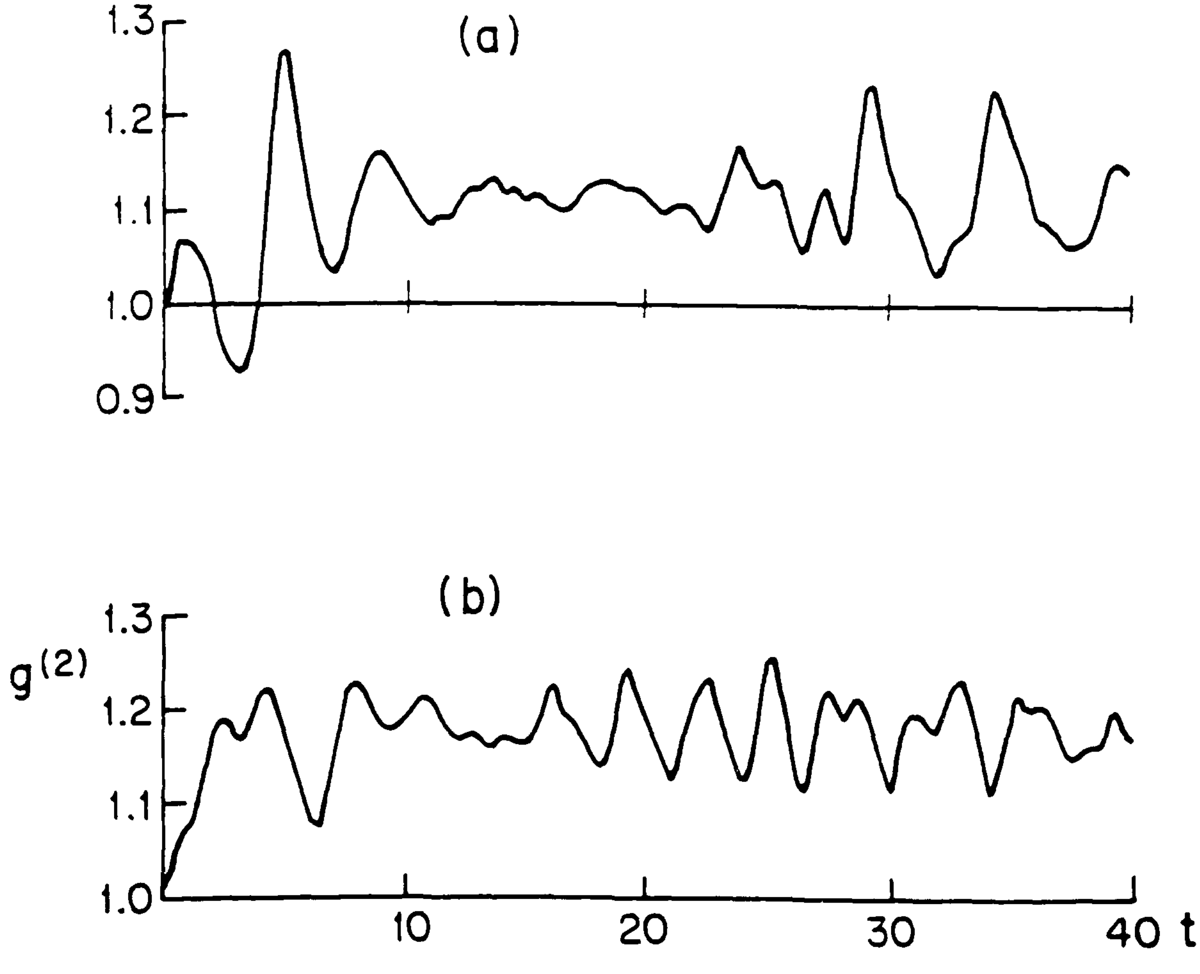


Fig. 9



OL/1113/86/2

TECHNICAL REPORT DISTRIBUTION LIST, GEN

	No. Copies
Office of Naval Research Attn: Code 1113 800 N. Quincy Street Arlington, Virginia 22217-5000	2
Dr. Bernard Douda Naval Weapons Support Center Code 50C Crane, Indiana 47522-5050	1
Naval Civil Engineering Laboratory Attn: Dr. R. W. Drisko, Code L52 Port Hueneme, California 93401	1
Defense Technical Information Center Building 5, Cameron Station Alexandria, Virginia 22314	12 high quality
DTNSRDC Attn: Dr. H. Singerman Applied Chemistry Division Annapolis, Maryland 21401	1
Dr. William Tolles Superintendent Chemistry Division, Code 6100 Naval Research Laboratory Washington, D.C. 20375-5000	1
Dr. David Young Code 334 NORDA NSTL, Mississippi 39529	1
Naval Weapons Center Attn: Dr. Ron Atkins Chemistry Division China Lake, California 93555	1
Scientific Advisor Commandant of the Marine Corps Code RD-1 Washington, D.C. 20380	1
U.S. Army Research Office Attn: CRD-AA-IP P.O. Box 12211 Research Triangle Park, NC 27709	1
Mr. John Boyle Materials Branch Naval Ship Engineering Center Philadelphia, Pennsylvania 19112	1
Naval Ocean Systems Center Attn: Dr. S. Yamamoto Marine Sciences Division San Diego, California 91232	1
Dr. David L. [illegible] Chemistry Division Office of Naval Research 800 North Quincy Street Arlington, Virginia 22217	1

ABSTRACTS DISTRIBUTION LIST, 056/625/629

Dr. J. E. Jensen
Hughes Research Laboratory
3011 Malibu Canyon Road
Malibu, California 90265

Dr. J. H. Weaver
Department of Chemical Engineering
and Materials Science
University of Minnesota
Minneapolis, Minnesota 55455

Dr. A. Reisman
Microelectronics Center of North Carolina
Research Triangle Park, North Carolina
27709

Dr. M. Grunze
Laboratory for Surface Science and
Technology
University of Maine
Orono, Maine 04469

Dr. J. Butler
Naval Research Laboratory
Code 6115
Washington D.C. 20375-5000

Dr. L. Interante
Chemistry Department
Rensselaer Polytechnic Institute
Troy, New York 12181

Dr. Irvin Heard
Chemistry and Physics Department
Lincoln University
Lincoln University, Pennsylvania 19352

Dr. K.J. Klaubunde
Department of Chemistry
Kansas State University
Manhattan, Kansas 66506

Dr. C. B. Harris
Department of Chemistry
University of California
Berkeley, California 94720

Dr. F. Kutzler
Department of Chemistry
Box 5055
Tennessee Technological University
Cookesville, Tennessee 38501

Dr. D. DiLella
Chemistry Department
George Washington University
Washington D.C. 20052

Dr. R. Reeves
Chemistry Department
Renssaeler Polytechnic Institute
Troy, New York 12181

Dr. Steven M. George
Stanford University
Department of Chemistry
Stanford, CA 94305

Dr. Mark Johnson
Yale University
Department of Chemistry
New Haven, CT 06511-8118

Dr. W. Knauer
Hughes Research Laboratory
3011 Malibu Canyon Road
Malibu, California 90265

ABSTRACTS DISTRIBUTION LIST, 056/625/629

Dr. G. A. Somorjai
Department of Chemistry
University of California
Berkeley, California 94720

Dr. J. Murday
Naval Research Laboratory
Code 6170
Washington, D.C. 20375-5000

Dr. J. B. Hudson
Materials Division
Rensselaer Polytechnic Institute
Troy, New York 12181

Dr. Theodore E. Madey
Surface Chemistry Section
Department of Commerce
National Bureau of Standards
Washington, D.C. 20234

Dr. J. E. Demuth
IBM Corporation
Thomas J. Watson Research Center
P.O. Box 218
Yorktown Heights, New York 10598

Dr. M. G. Lagally
Department of Metallurgical
and Mining Engineering
University of Wisconsin
Madison, Wisconsin 53706

Dr. R. P. Van Duyne
Chemistry Department
Northwestern University
Evanston, Illinois 60637

Dr. J. M. White
Department of Chemistry
University of Texas
Austin, Texas 78712

Dr. D. E. Harrison
Department of Physics
Naval Postgraduate School
Monterey, California 93940

Dr. R. L. Park
Director, Center of Materials
Research
University of Maryland
College Park, Maryland 20742

Dr. W. T. Peria
Electrical Engineering Department
University of Minnesota
Minneapolis, Minnesota 55455

Dr. Keith H. Johnson
Department of Metallurgy and
Materials Science
Massachusetts Institute of Technology
Cambridge, Massachusetts 02139

Dr. S. Sibener
Department of Chemistry
James Franck Institute
5640 Ellis Avenue
Chicago, Illinois 60637

Dr. Arnold Green
Quantum Surface Dynamics Branch
Code 3817
Naval Weapons Center
China Lake, California 93555

Dr. A. Wold
Department of Chemistry
Brown University
Providence, Rhode Island 02912

Dr. S. L. Bernasek
Department of Chemistry
Princeton University
Princeton, New Jersey 08544

Dr. W. Kohn
Department of Physics
University of California, San Diego
La Jolla, California 92037

ABSTRACTS DISTRIBUTION LIST, 056/625/629

Dr. F. Carter
Code 6170
Naval Research Laboratory
Washington, D.C. 20375-5000

Dr. Richard Colton
Code 6170
Naval Research Laboratory
Washington, D.C. 20375-5000

Dr. Dan Pierce
National Bureau of Standards
Optical Physics Division
Washington, D.C. 20234

Dr. R. Stanley Williams
Department of Chemistry
University of California
Los Angeles, California 90024

Dr. R. P. Messmer
Materials Characterization Lab.
General Electric Company
Schenectady, New York 22217

Dr. Robert Gomer
Department of Chemistry
James Franck Institute
5640 Ellis Avenue
Chicago, Illinois 60637

Dr. Ronald Lee
R301
Naval Surface Weapons Center
White Oak
Silver Spring, Maryland 20910

Dr. Paul Schoen
Code 6190
Naval Research Laboratory
Washington, D.C. 20375-5000

Dr. John T. Yates
Department of Chemistry
University of Pittsburgh
Pittsburgh, Pennsylvania 15260

Dr. Richard Greene
Code 5230
Naval Research Laboratory
Washington, D.C. 20375-5000

Dr. L. Kesmodel
Department of Physics
Indiana University
Bloomington, Indiana 47403

Dr. K. C. Janda
University of Pittsburg
Chemistry Building
Pittsburg, PA 15260

Dr. E. A. Irene
Department of Chemistry
University of North Carolina
Chapel Hill, North Carolina 27514

Dr. Adam Heller
Bell Laboratories
Murray Hill, New Jersey 07974

Dr. Martin Fleischmann
Department of Chemistry
University of Southampton
Southampton 509 5NH
UNITED KINGDOM

Dr. H. Tachikawa
Chemistry Department
Jackson State University
Jackson, Mississippi 39217

Dr. John W. Wilkins
Cornell University
Laboratory of Atomic and
Solid State Physics
Ithaca, New York 14853

DL/1113/86/2

ABSTRACTS DISTRIBUTION LIST, 056/625/629

Dr. R. G. Wallis
Department of Physics
University of California
Irvine, California 92664

Dr. D. Ramaker
Chemistry Department
George Washington University
Washington, D.C. 20052

Dr. J. C. Hemminger
Chemistry Department
University of California
Irvine, California 92717

Dr. T. F. George
Chemistry Department
University of Rochester
Rochester, New York 14627

Dr. G. Rubloff
IBM
Thomas J. Watson Research Center
P.O. Box 218
Yorktown Heights, New York 10598

Dr. Horia Metiu
Chemistry Department
University of California
Santa Barbara, California 93106

Dr. W. Goddard
Department of Chemistry and Chemical Engineering
California Institute of Technology
Pasadena, California 91125

Dr. P. Hansma
Department of Physics
University of California
Santa Barbara, California 93106

Dr. J. Baldeschwieler
Department of Chemistry and Chemical Engineering
California Institute of Technology
Pasadena, California 91125

Dr. J. T. Keiser
Department of Chemistry
University of Richmond
Richmond, Virginia 23173

Dr. R. W. Plummer
Department of Physics
University of Pennsylvania
Philadelphia, Pennsylvania 19104

Dr. E. Yeager
Department of Chemistry
Case Western Reserve University
Cleveland, Ohio 41106

Dr. N. Winograd
Department of Chemistry
Pennsylvania State University
University Park, Pennsylvania 16802

Dr. Roald Hoffmann
Department of Chemistry
Cornell University
Ithaca, New York 14853

Dr. A. Steckl
Department of Electrical and Systems Engineering
Rensselaer Polytechnic Institute
Troy, NewYork 12181

Dr. G.H. Morrison
Department of Chemistry
Cornell University
Ithaca, New York 14853